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Research Article

Key Parameter Study of 65Mn Steel in Warm Rolling

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Abstract: For study warm rolling process, warm compression experiment of ferrite combined with pearlite colony was conducted using the Gleeble-3500 thermal/mechanical simulator system. The warm deformation was carried out at temperature (500~700°C) and the strain rate (0.001~10/sec). Based on the flow stress data, the key parameter was calculated. The results show that the warm-working process of carbon steel conforms to hyperbolic sine equation. The relationship of $\dot{\varepsilon}$ and T could be described by parameter Z (temperature compensation of strain rate factor). The value of apparent n (stress index) and Q (deformation activation energy) was calculated, the draught pressure calculated was 1.87×10^4 t during warm rolling process at 600°C.

Keywords: Activation energy, high-carbon steel, rolling force, strain, worm rolling

INTRODUCTION

Along with the economic and social development, steel materials development faced with new challenges. It is an important development direction for recent steel materials to produce steel materials of excellent performance, low cost and saving energy consumption by improving processing technology greatly to improve the performance of the steel materials, avoiding alloying tendency and reducing production energy consumption (Xu, 2010, 2011). In order to achieve this goal, steel materials in all kinds of process conditions of the deformation behavior and organizational change has been researched a lot in recent years. Numerous studies have shown that: Meysami and Mousavi (2011) and Song *et al*. (2004) At medium temperature or the cold high Z factor condition (Dudova *et al*., 2010; Niang *et al*., 2012), Super-Refine Structure can be obtained without phase change through big strain processing, this plays an important role in enhancing the material properties and avoiding the tendency of alloying and it is of great significance to improve the circulation of the materials and save resources (Timokhina *et al*., 2004; Yunusova *et al*., 2007). Warm working is materials plastic forming between the temperature of hot working temperature T>0.6 Tm, Tm is the metal melting point of absolute temperature) and cold working (temperature $T<0.3T_m$). The researches on steel temperature processing at home and in abroad focus on preparation of ultrafine organization of new material in the laboratory, to realize the industrial application of warm working technology, we should study the numerous problems involved in materials plastic forming.

The mechanical behavior of deformation, whose main characterization is the flow stress (Fu *et al*., 2011), is the basic premise and important basis in plastic forming process analysis, process design, equipment selection and design. This study adopts cylindrical uniaxial compression experiment to research medium carbon steel during warm rolling, calculate the key parameters of warm rolling. The results can be used as basis of the warm rolling process analysis, process design and equipment improvement.

EXPERIMENT PROCEDURE AND RESULTS

The chemical compositions of the carbon steel of experiment (Mass fraction %) are: C 0.65, Si 0.26, Mn 1.10, Cr 0.02, V 0.02. The samples are processed into φ8×12 mm, surface of the specimen should be of good finish, the ends should be parallel and smooth and there are no cracks and other defects. The experiment of the compression deformation is performed on Gleeble-3500 thermal simulation machine.

The isothermal compression experiment process is shown in Fig. 1. The samples were heated to 950°C with speed of 20°C /sec and hold at the temperature for 3 min, then cooled it to deformation temperature (550~700°C) with the speed of 10°C/sec, then kept it at the temperature for 30 sec, then make compression test with strain rate (0.001~1/sec) and deformation amount 70%.

The stress-strain curve is showed by the Fig. 2. From the drawing it could be found that the materials expressed work-hardening at the beginning and then the

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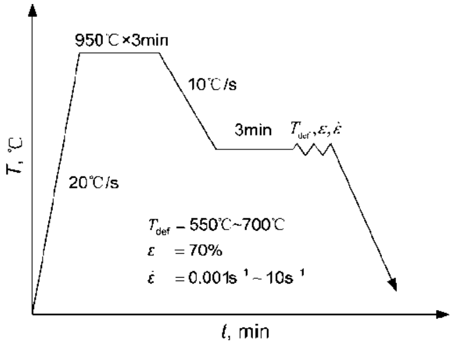

Fig. 1: Process of the compression test

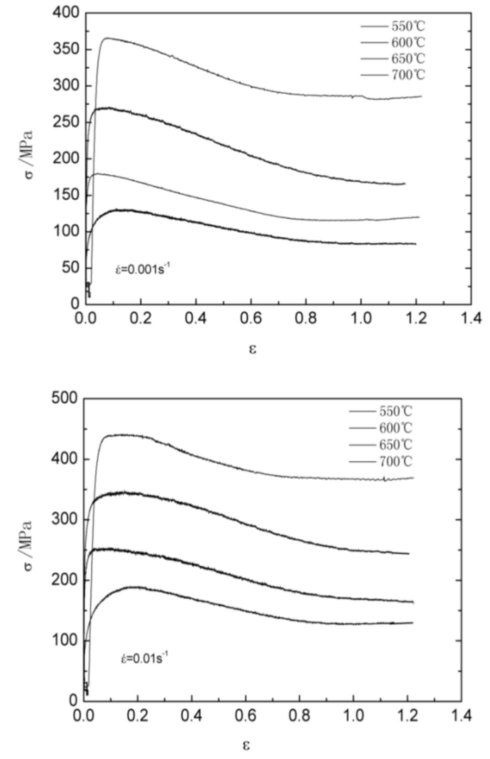

Fig. 2: Flow stress curves of warm-deforming

work-hardening slow down, when the stress passed the peak, steel softened strongly and the stress fall down.

At the last, the materials being in the steady state and the flow stress without change (Abou-Msallem *et al*., 2010; Wang *et al*., 2012). For the soften mechanism are dynamic recrystallization and cementite spheroidization, it is controlled by thermal activation.

Parameter and warm rolling equation: Flow stress is the one important performance of metal various performance index, the flow stress intensity of iron and steel material directly affects the safe operation of the equipment, it is key that guarantee the fully plastic deformation occurred while processing. Furthermore, it also has a great influence to the plastic processing performance and prediction precision of finite element simulation precision.

Warm deformation is described using constitutive equations that included deformation activation energy Q and temperature T by Solhjoo and Ebrahimi (2010):

$$\dot{\varepsilon} = \mathrm{A} f(\sigma)\exp\left(-\frac{\mathrm{Q}}{\mathrm{R}T}\right) \tag{1}$$

where,

$\dot{\varepsilon}$ = Rate of deformation, s^{-1}
Q = Deformation activation energy, kJ/mol, (reaction the hard degree of material thermal deformation)
A = Constant
R = Gas constant
T = Thermodynamics temperature, K

According to the reference, stress function in formula (1) has three common forms as follow:

$$f(\sigma) = \sigma^{\mathrm{n}} \tag{2}$$

$$f(\sigma) = \exp(\beta\sigma) \tag{3}$$

$$f(\sigma) = [\sinh(\alpha\sigma)]^{\mathrm{n}} \tag{4}$$

Above the formula, the relationship between (α, β, n) is meet the formula as: α = β/n. The σ is the peak stress or steady stress, or corresponding to a stress that specified strain.

The strain rate is controlled by heating activation process when the materials occur plastic deformation control, the relationship between strain rate and temperature can indicated by the temperature compensation of strain rate factor Zener-Hollomon parameters (Z parameters), that is:

$$Z = \dot{\varepsilon}\exp\left(\frac{\mathrm{Q}}{\mathrm{R}T}\right) \tag{5}$$

Z parameter is used to characterization of deformation temperature and deformation rate effecting on the integrative action of deformation process.

where, Z is temperature compensation of strain rate factor, R is gas constant.

Put the formula (4) in the (1) as follow:

$$\dot{\varepsilon} = \mathrm{A}[\sinh(\alpha\sigma)]^{\mathrm{n}}\exp\left(-\frac{\mathrm{Q}}{\mathrm{R}T}\right) \tag{6}$$

Put the formula (6) in the (5) as follow:

$$Z = \mathrm{A}[\sinh(\alpha\sigma)]^{\mathrm{n}} \tag{7}$$

$$\sinh(\alpha\sigma) = (Z/\mathrm{A})^{1/\mathrm{n}} \tag{8}$$

According to the definition of hyperbolic sine function to:

$$\sin^{-1}(\alpha\sigma) = \ln\left[\alpha\sigma + \left((\alpha\sigma)^2 + 1\right)^{1/2}\right] \tag{9}$$

So, the stress is:

$$\sigma = \frac{1}{\alpha}\ln\left\{(Z/A)^{1/n} + \left[(Z/A)^{2/n} + 1\right]^{1/2}\right\} \tag{10}$$

Then, put the formula (2), (3) in the (1) respectively as follow:

$$\dot{\varepsilon} = A\sigma^{n}\exp\left(-\frac{Q}{RT}\right) \tag{11}$$

$$\dot{\varepsilon} = A\exp(\beta\sigma)\exp\left(-\frac{Q}{RT}\right) \tag{12}$$

On the condition of constant temperature (Jozef *et al*., 2010), both sides of the formula (11) (12) is logarithmic transformation respectively and take the function relationship between In $\dot{\varepsilon} - In\sigma$ and $\dot{\varepsilon} - In\sigma$, then the two formulas are calculated partial derivative by In$\dot{\varepsilon}$ respectively:

$$n = \frac{1}{\left[\partial(\ln\sigma)/\partial(\ln\dot{\varepsilon})\right]_T} \tag{13}$$

$$\beta = \frac{1}{\left[\partial\sigma / \partial(\ln\dot{\varepsilon})\right]_T} \tag{14}$$

In$\dot{\varepsilon}$ as the horizontal ordinate, lnσ_p and σ_p as the vertical ordinate respectively, plotting the figures according to experimental data as Fig. 3 shows.

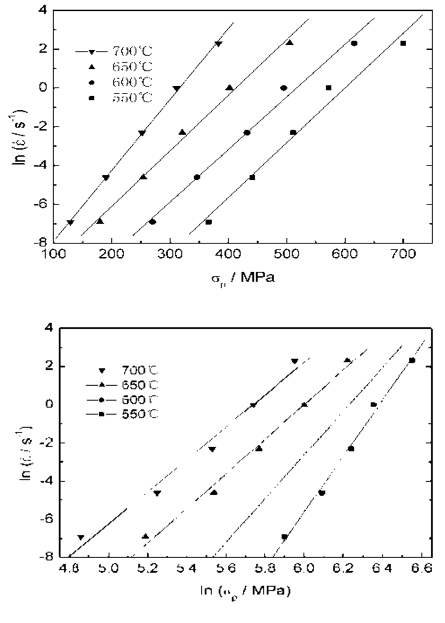

Fig. 3: Relationship between $\dot{\varepsilon}$ and σ_p

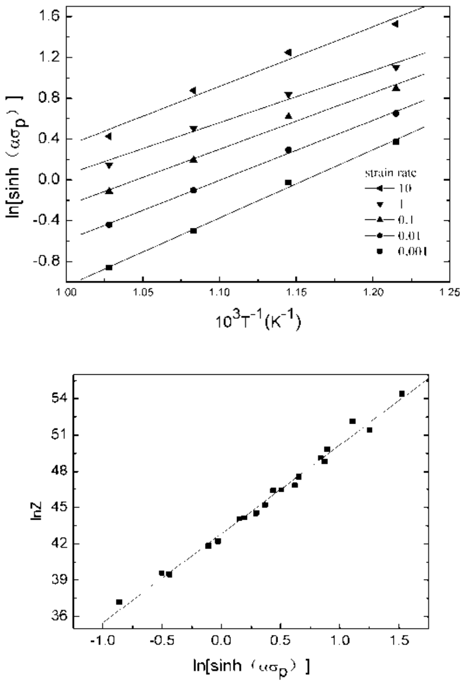

Fig. 4: Relationship between T^{-1}, lnZ and lnsinh(a•σp)

The linear slope is calculated using the method of least squares and take the average value of slope reciprocal, so it can be obtain the values that n = 9.65 and β = 0.3077, then get the α = 0.003189.

On both sides of the exponential for (6) as follow:

$$-\ln A + \ln\dot{\varepsilon} + \frac{Q}{RT} = n\ln\left[\sinh(\alpha\sigma)\right] \tag{15}$$

When the strain rate is certain, the partial derivative of (6) is:

$$Q = R \times n \times \left\{\frac{\partial\ln[\sinh(\alpha\sigma)]}{\partial(1/T)}\right\}_{\dot{\varepsilon}} \tag{16}$$

$$Q = R \times n \times n_1 \tag{17}$$

It can be get the relational curve of In [sinh ($\alpha\sigma_p$)] and 1/T using the method of least squares, as Fig. 4 shows.

The average gradient of line serves as n1, put the corresponding value in the formula (17), it is computed that the deformation activation energy = 356.525. It can be computed the value of constant A substituting data into the formula (16). Figure 4 shows the regressive line and its intercept is the value of lnA. The value of A is 4.043×10^{18}.

So, the warm deformation equation of the steel 65 Mn is:

$$\dot{\varepsilon} = 4.043 \times 10^{18}\,[\sinh(0.003189\sigma]^{9.65} \exp(-3565325/RT) \tag{18}$$

The Z parameter of warm deformation for the steel 65 Mn is:

$$Z = \dot{\varepsilon}\,\exp\left(\frac{356525}{RT}\right) \tag{19}$$

So, the warm rolling equation of the steel 65 Mn using Z parameter expression is:

$$\sigma = 313.578\ln\left\{\left[Z/(4.043\times10^{18})\right]^{0.1036} + \left\{\left[Z/\left(4.043\times10^{18}\right)\right]^{0.2073} + 1\right\}^{0.5}\right\} \tag{20}$$

Rolling force: The rolling pressure is the most important process parameters in the steel rolling production (Zhu *et al*., 2001), it is also the important original parameters to develop process system and adjustment of the mill, strengthening the rolling, improve the quality of products, expand the product range, fully rational digging equipment potential and realize the computer control of production process. The rolling force calculation formula is:

$$P = FP_{\mathrm{m}} \tag{21}$$

In the formula (21):

$$F = b_{\mathrm{m}} l' \tag{22}$$

$$P_m = n'_\sigma k \tag{23}$$

where,

P = Rolling pressure, MN

F = Contact area of work piece and roller, m^2

P_m = Average unit pressure, MPa

b_m = Mean width, m

l′ = Horizontal plan of contact arc length for the work piece and roller, m

n'_σ = Influence coefficient of stress condition

k = The metal plastic deformation resistance, MPa

By Sims' formula known (Sun *et al*., 2009):

$$n'_\sigma = \frac{\pi}{2\sqrt{\frac{1-\varepsilon}{\varepsilon}}}\arctan\sqrt{\frac{\varepsilon}{1-\varepsilon}} - \frac{\pi}{4} - \sqrt{\frac{1-\varepsilon}{\varepsilon}}$$

$$\sqrt{\frac{R}{h_1}}\,In\,\frac{h_\gamma}{h_1} + \frac{1}{2}\sqrt{\frac{1-\varepsilon}{\varepsilon}}\sqrt{\frac{R}{h_1}}\,In\,\frac{1}{1-\varepsilon} \tag{24}$$

In the formula (24):

$$\frac{h_\gamma}{h_1} = 1 + \frac{R}{h_1}\gamma^2 \tag{25}$$

where,

ε = Deformation degree

R = Semi diameter of roller, mm

h_1 = Exit thickness, mm

h_γ = Neutral surface thickness, mm

γ = Neutral angle

Related parameter value is computed according to hot rolling production line of 1580 from Qian an Iron & Steel Co.

where: entry thickness (h0) is 40 mm, exit thickness (h1) is 12 mm, deformation degree (ε) is 70%, work piece width (b_m) is 1248 mm, semidiameter of Roller (R) is 710 mm.

The Related parameter value is put into Sims' formula, it could be obtain that:

$$n'_\sigma = 1.68 \tag{26}$$

Comprehensive consideration the results of mechanics performance for 65 Mn steel, it was found that the 65 Mn steel comprehensive performance is better when the deformation temperature is 600°C and deformation rate is 10/sec. Therefore, the peak stress (587 MPa) is deformation resistance when deformation temperature of 600°C, deformation rate for 10/sec, it is substituted calculation that $P_m = 986.16$ MPa. From the geometrical relationship, it can be obtained that:

$l' = 0.152m$. Put the formula (28) in the (22) it could be got that:

$$F = b_m \times l' = 0.19\ \mathrm{mm}^2 \tag{27}$$

Put the formula (27) (29) in the (21) respectively it is as follows:

$$P = FP_{\mathrm{m}} = 1.87\times10^4\ \mathrm{t} \tag{28}$$

CONCLUSION

- At every test temperature, with the rate of deformation increased, the peak stress was higher, steel softened more strongly after the peak stress at 550°C strain rate, the peak stress was the highest and the stress was softened most strongly subsequently
- The warm-working process of carbon steel conforms to hyperbolic sine equation. The relationship of $\dot{\varepsilon}$ and T could be described by parameter Z. The value of apparent stress index n and deformation activation energy Q was calculated
- The pressure of two types carbon steel warm rolling was calculated at 600°C, the rolling force is 1.87×10^4 t. The pressure of warm rolling is heavier

than hot working, so that warm rolling is difficult than normal way.

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